Chapter Three: Hyperspectral Imaging in Long Valley Caldera: Volcano-Associated Biological Communities

1.0 Introduction

Most volcanic areas in the world host communities of vegetation thriving, modified or dying in response to extremes of temperature, acidity/alkalinity, and noxious degassing. Few are monitored and studied as well as the Long Valley Caldera in California, USA. Increased volcanic activity in Long Valley in the early 1980's led to an intense monitoring program that has revealed much about the region's volcanic, tectonic, and hydrothermal processes. Long Valley is unique in the intensity and duration of monitoring and characterization, and hence is ideal for testing and evaluating new technologies such as hyperspectral imaging.

This chapter addresses the application of hyperspectral remote sensing for mapping and evaluation of biological communities affected by, and in some cases, thriving in areas of volcanic activity. In Long Valley, these communities include alpine forests exposed to sublethal-lethal levels of volcanic CO_2 exhalation; trees and shrubs on toxic acid-loaded soils; prematurely senescent grasses in fumarolic fields, and microorganisms within hydrothermal pools, creeks, and moist soils. While such communities have been studied previously, the synoptic coverage provided by remote sensing creates a view of these communities as parts of a larger volcanic system, rather than as individual ecosystems.

The general goal of this study was to detect and map several of these volcanic plant communities in as much detail as possible, both spatially and temporally. Secondary goals included determining the physiological state of individual organisms or communities and determining whether unique "stress" signatures for biological populations can be extracted from hyperspectral data. Finally, an evaluation of remote characterization of biological communities in volcanic environments is proffered, with an emphasis on hyperspectral capabilities. More traditional techniques for field studies of communities are time-consuming and site-intensive, but remote sensing, especially hyperspectral imaging, allows us to characterize patterns and boundaries throughout large systems. Sources of physiological stress due to volcanic activity are more easily determined with hyperspectral imagery because plants, geologic structures, geochemical mineralization, and volcanic phenomena are all imaged simulataneously, and are readily identified and mapped with these data. Hyperspectral remote sensing provides an interdisciplinary view of Long Valley Caldera based on simultaneous geological and biological analyses of the same dataset.

The use of remote sensing for mapping and characterization of volcanogenic biological communities has important applications for monitoring hazardous volcanic activities not just in the United States, but especially in developing nations with little capital or infrastructure available for ground-based monitoring efforts. These data are also important for resource exploration in volcanic areas (including mining, geothermal prospecting, and bio-prospecting). Studies of biological communities linked to volcanic phenomena in a well-known and well-studied region such as Long Valley Caldera should lead to better and quicker understanding of such communities in other poorly studied, remote volcanic environments.

2.0 Background

2.1 Long Valley Caldera

2.1.1 Formation and petrology

Long Valley Caldera is one of three active calderas in the contiguous United States and is located in central California (Figure 3-1). It formed approximately 760,000 years ago in a violent eruption that expelled > 600 km^3 of ash and lava (Bailey et al, 1976) over a period of several months (McConnel et al, 1995; Hildreth and Mahood, 1986). Since this event, several successive eruptive events have covered the region with other volcanic flows and domes. Silica-content, permeability, and degree of glassiness vary across these flows. The youngest flows are in the western caldera where the most recent activity dates to only ~500 years ago. The N-S trending Mono-Inyo Chain includes the rhyodacitic Mammoth Mountain located at the far southern end of the chain.

2.1.2 Hydrothermal system chemistry and dynamics

The hydrothermal system seen today is the vestige of a 40ka peak in activity (Sorey, 1985), in which hydrothermal waters in the caldera appear to source in the west from a recharge zone at the Sierra front. The waters flow down along range front faults and caldera ring fractures and are heated by a magmatic source at depth (Blackwell, 1985; Sorey, 1985). Lateral transport of these waters appears to be at approximately 1 km depth, along or just within the top of the Bishop Tuff. Temperatures at depth have been measured directly in wells at up to 214°C at one site, though geothermometry suggests source reservoirs reach 240°C (Sorey, 1991). No liquid discharge of hot waters is known west of Highway 395, with the exception of the Reds Meadow thermal creek on the far western flank of Mammoth Mt. Permeability in the Long Valley Caldera geothermal system is governed by transport and discharge along various fault systems in the western and central caldera. Once at the surface, hydrothermal waters flow south-eastwards in a plume-like fashion, that covers the eastern caldera with a slightly thermal, marsh-like environment. Saline, sodium-bicarbonate waters are predominantly neutral to alkaline throughout the caldera. They and rarely reach boiling point and temperatures range from ~79-93°C in the hotter central regions and down to 20-25°C in the eastern caldera. There are extensive deposits of both travertine and sinter in these areas, though present deposition is primarily travertine (Lipshie, 1976). Hydrothermal alteration products generally consist of argillic phase kaolinite and montmorillinite with localized distributions of advanced argillic alunite and pyrophyllite.

Fumarolic discharge occurs, or has occurred, in several locales around the caldera, especially along normal faults in Fumarole Valley, formation contacts at Basalt Fumarole, faults on the flanks of Mammoth Mt., and faults of the Discovery Fault Zone. Advanced argillic alteration predominates locally in these regions, typically with high temperature sulfate alunite surrounded by kaolinite and montmorillinite.

The prolific hot pools and creeks are characterized by abundant hydrothermal alteration of surrounding rocks and soils, as well as simple vegetation zonation patterns. The waters themselves are inhabited by an array of thermophilic algae and bacteria. Grasses surround the pools and creeks, which are in turn encompassed by a narrow swath of rabbit brush (*Chrysothamnus nauseosus*). The rabbitbrush gives way to sagebrush (*Artemesia tridentata*) and occasional Juniper (*Juniperus osteosperma*) and Pinyon pine (*Pinus monophylla*).

2.1.3 Local structure

Regional structure in eastern California has been strongly influenced by Basin and Range extension and Eastern California Shear Zone tectonics. Locally, Long Valley Caldera is bounded on the west by ring fractures and the large northwest trending normal faults of the Sierra Nevada Fault Zone that have experienced up to 2000 meters of normal displacement (Bailey, 1989; Unruh, 1991). Smaller northwest trending normal faults cut the central resurgent dome region while ring fractures rim the eastern boundary of the caldera (Bailey, 1989). Recent work by Prejean(2001) also confirms the existence of east-west trending strike-slip faults in the southern moat (Rundle and Whitcomb, 1984) On a still smaller scale, the western caldera is populated by northwest trending normal faults, north-south trending normal faults and northeast trending transtensional faults (Fink, 1985; Mastin and Pollard, 1988; Suemnicht and Varga, 1988; Bailey, 1989). The intersections of these fault zones result in enhanced vertical permeability, which provides foci for movement of hydrothermal waters and zones of discharge, and profoundly affects the formation of the Inyo volcanic chain by providing conduits for magma migration.

2.2 Previous remote sensing studies

The material mapping abilities and synoptic, multi-temporal, system-scale coverages acquired with satellite and air-based sensors make remote sensing a standard tool for most volcanological monitoring and study programs. However, Long Valley caldera has received limited geological study via standard remote sensing techniques, and even fewer biological studies. The only substantial biologically-inclined studies of Long Valley are hyperspectral studies done in the western caldera at Mammoth Mt. De Jong (1998), Hausback et al. (1998) and Sorey et al. (1998) used hyperspectral imaging of Mammoth Mt. to map CO_2-induced tree-kills on the volcano's flanks, while DeJong and Chrien (1995) attempted to map CO_2 emissions directly, but with limited success.

2.3 Why Hyperspectral?

Why acquire hyperspectral imagery of Long Valley Caldera? Fundamentally, the data acquired by such instruments are notoriously large and time consuming to process and analyze, but advances in the way the data are reduced and analyzed have made hyperspectral data managable and efficient, while the growing size of affordable disk storage makes managing and manipulating the data physically attainable. While multispectral instruments produce much smaller datasets, hyperspectral imagers are capable of addressing far more complex questions than multispectral instruments. As an example, multispectral satellite instruments can capture and map a certain level of complexity within vegetation and ecosystems, by using wavelength band ratio calculations such as the Normalized Difference Vegetation Index (NDVI) to detect and map degree of greenness in satellite data such as Landsat. Degree of greenness is correlated to amount of chlorophyll, which is one measure of plant health. However, to study the complexity of grass phenology in the vicinity of spatially restricted fumaroles, or conifer health on a tree by tree basis, an instrument with fine spectral sampling and small pixels capable of capturing individual organisms and small spatial areas is needed. The coarse spatial resolutions of Landsat and similar satellites cannot image individual trees, and their sparse and wide spectral bands cannot capture the rare but unique biochemical absorptions in vegetation and other organics.

Mapping microorganisms in small hot pools and creeks around Long Valley and the restricted spatial distributions of various plants in response to geological forcing such as noxious gasses and extreme temperature requires a hyperspectral imager. Hyperspectral instruments routinely acquire data at spatial resolutions as fine as 2-3 meters and spectral resolutions of 10nm. This allows for the measurement of single organisms, or small groups within an ecosystem. It also provides spectral detail that can often identify classes (sometimes species) of organisms such as algae, grass, shrubs, conifers, and deciduous trees, as well as information on physiological health. Because such imagers are primarily airborne, they provide the flexibility to fly in the season and at the time most suitable for vegetation characterization.

3.0 General methods

3.1 HyMap data acquisition

Until 1999, there were no hyperspectral data of Long Valley Caldera as a whole, although several NASA sponsored Advanced Visible Infrared Imaging Spectrometer (AVIRIS) missions had covered the much smaller Mammoth Mountain area and some areas in the eastern caldera. The first AVIRIS image was taken in 1992, with subsequent images taken yearly after that. Though this dataset has an impressive temporal resolution, its spatial resolution is approximately 17 m. While useful vegetation studies have been done with data at this spatial resolution, 17 m is generally considered quite coarse for physiological interpretations of plant properties due to both the spatial and temporal variability encountered in biological communities.

To obtain finer pixel resolution for vegetation communities as well as primary hyperspectral coverage of the entire caldera, an acquisition was flown on September 7, 1999 with the Australian HyMap sensor (Integrated Spectronics, Ltd.). The acquisition covered approximately 540km^2 between latitudes 37° 30" to 37° 36" N and longitudes 118° 42" to 119° 04" W (Figure 3-1). Seven east-west flightlines have a spatial resolution that varies from 3 to 5m depending on local topography (elevation ranges from 2070m on the caldera floor to about 3300m in the Sierra and at Mammoth Mountain). HyMap samples the electromagnetic spectrum from 450 to 2500 nm, in 126 separate but contiguous wavelength bands from 13 to 17 nm wide. The instrument was flown aboard a twin-engine Cessna with complete radiometric and spectral calibration and simultaneous DGPS data acquisition. The dataset was acquired as part of a group-shoot that included several other U.S. governmental, educational, and commercial entities and was organized by Analytical Imaging and Geophysics (AIG) in Boulder, CO, USA and the HyVista Corporation in Sydney, Australia.

3.2 Spectral pre-processing of the HyMap data

Primary processing and analysis was done with the software package ENVI©. The data were delivered as raw radiance-at-sensor in $\mu W/cm^2/sr^{-1}/nm^{-1}$ and as apparent reflectances calculated from the radiance data using the radiance transfer code ATREM (Atmospheric Removal) (Gao, 1993). Further atmospheric and machine artifacts were minimized using the EFFORT algorithm (Empirical Flat Field Optimal Reflectance Transformation) (Boardman, 1998) to smooth the spectra. Only the EFFORT-corrected apparent reflectances were used in this study.

The reflectance data were spatially and spectrally subset to isolate unique spectral populations of pixels within an image. The data were spectrally subset first. Traditionally, most vegetation work is done within the visible and near-infrared regions of the electromagnetic spectrum, because most vegetation pigments have characteristic absorptions in the visible, while the internal structure of plant leaves and needles is often expressed as distinctive spectral geometries in the Visible-Near Infrared (VNIR). Typical vegetation spectra include the "red-edge" which extends from approximately 0.67 µm to just below 0.90 µm and the near-infrared plateau which extends from approximately 0.90 µm to 1.35 µm (Figure 3-2). Plants also have distinctive spectral geometries in the Short-Wave Infrared (SWIR) region. Cellulose, lignin, and several other carbohydrates and secondary compounds absorb in this part of the EM spectrum. Both regions (the VNIR and SWIR) were used in this study, though they were processed separately. Some analyses were carried out on all 126 bands of HyMap data, minus four water bands, while other analyses were applied separately to two portions: a VNIR portion (0.45 – 1.9 µm) and a SWIR portion (2.0-2.5 µm).

The data were spatially subset to include only those regions, features, or phenomena of interest. Each HyMap flightline was approximately 32 km long and 2.5 km wide with a 25% overlap between lines. Images of entire flightlines contained approximately 1.2 GB of data which limited the analysis of entire flightlines due to the CPU and disk-storage space required for processing. More importantly, spectral variability within a scene increases with the size of that scene, but statistical algorithms used to analyze these data rely on reducing spectral variability to discriminate dominant scene materials. The less variability encountered by the algorithms, the better are the results for determining dominant scene materials. The subsets used in this study are roughly 2-3 km long and a maximum of 2.5 km wide.

4.0 Spectroscopic mapping of volcanogenic CO_2-induced tree-kills: Mammoth Mountain, CA

4.1 Introduction

The unprecedented death of tens of hectares of alpine forest on the flanks of Mammoth Mountain, CA garnered early attention from California state forest workers and Mammoth Mt. ski personnel. All trees and other plants, regardless of species, began dying in the spring and summer of 1990 on both state forest lands (including Horseshoe Lake), and in-bounds of Mammoth Ski, in the middle of well-groomed ski-runs. Two years later, a hyperspectral imager (AVIRIS) was flown over the mountain in hopes that the fine spatial and spectral sampling of this instrument might elucidate the boundaries of the kills and possibly their future trajectory. It was suggested that spectral signatures extracted from tree-kills within the imagery or field spectra collected from within the kills, could be used to map the spatial extent of these kills. Perhaps physiological properties could also be extracted from the signatures and stressor correlations made. However, limited work was done with this initial dataset and the subsequent AVIRIS missions flown over Mammoth due to poor signal-to-noise ratio (SNR) in the short-wave infrared and the 17 m pixel size.

To take a fresh look at Mammoth Mt. and to readdress the hyperspectral mapping of its fairly extensive CO_2-induced tree-kills, HyMap was flown in 1999 at a spatial resolution averaging 3.5 meters and an average SNR of 1000:1. I used the HyMap imagery to map, quantify, and examine the tree-kills on Mammoth, to investigate the physiological state of Mammoth tree communities via their spectral signatures, and to determine if there are signatures unique to particular stressors, i.e. is there a characteristic signature or set of absorptions unique to CO_2 vs. a signature unique to drought stress, fire, avalanche, etc.? Secondarily, I evaluated several different methods for the analysis of hyperspectral data in support of general biological mapping.

Several new techniques were used to accurately identify the boundaries of the tree-kill at Horseshoe Lake spectroscopically, and to determine whether incipient kill is discernable from the data. The Horseshoe Lake tree-kill is mapped four separate ways, involving different degrees of difficulty and time in processing. The pros and cons of each method are discussed, and the most straightforward way to spectrally map tree-kill boundaries is suggested for use on other less studied and less accessible volcanoes around the world.

4.2 Background: Mammoth Mountain re-awakens

4.2.1 Seismic swarms, magma on the move, and unprecedented tree death

In May 1989, a swarm of small magnitude earthquakes began in the east-central region of the Sierra Nevada in the state of California. The swarm was located beneath the Pleistocene-aged Mammoth Mountain, a rhyodacitic stratovolcano on the southwestern rim of the much larger, Long Valley caldera (Figure 3-1). The cumulative magnitude of the six-month long swarm corresponded to the moment of a single M~ 4.0 earthquake (Hill et al., 1990). The swarm contained both spasmodic bursts and events enriched in low-frequency energy: these types of earthquakes are rarely seen in purely tectonic environments. The early earthquakes were probably due to a magmatic dike intrusion at depth (Hill et al., 1990) and indicate the magma probably moved from initial depths of 7-9km to within approximately 1 km of the mountain's surface over the six month time period (Prejean, 2001). The later, shallower events were concentrated on two half-ring structures that may represent stress concentrations above an intruded pocket of magma (Nettles and Ekstrom, 1998).

The following spring (1990), unusually heavy loss of needles by pine trees was observed at several places on Mammoth Mountain by U.S. Forest Service personnel (Farrar et al., 1995), especially surrounding the popular recreation area of Horseshoe Lake. That spring (1990), approximately 4 ha of trees were dead at Horseshoe Lake alone, affecting all species of trees and other forest vegetation. The tree-kill continued to grow in size each spring, albeit quite slowly. In spring and summer 1994, another huge die-off added an additional 7 ha of dead trees. Since 1995, the Horseshoe Lake tree-kill area appears to have remained the same size, though recent spectroscopic analyses suggest that the kill may be expanding slowly (Martini, 2000). Tree-kills also occurred on other parts of the mountain and they also doubled in size from 1994 to 1997 from a total of approximately 20 ha to 40.5 ha (Hausback et al., 1998). Figure 3 shows the locations and rough boundaries of the major tree-kills on Mammoth Mountain.

4.2.2 Source of tree-death: Volcanogenic CO_2

Tree morbidity was first linked conclusively to massive CO_2 exhalation by Farrar et al. (1995). Other workers have detailed the likely volcanogenic source of CO_2; its paths of diffusion, generation, chemistry, behavior in the near subsurface, surface and air; spatial distribution of flux zones; temporal flux behavior; and dependency on local climatic variables (Sorey et al., 1998, 1999; McGee and Gerlach, 1998; Gerlach et al., 1999; Rogie et al., 2000, 2001). It is difficult to explain the large volume of gas currently fluxing from Mammoth with only the 1989 intrusion. Instead, Sorey and others suggest that CO_2 travels up along pre-existing faults and fractures from a semi-sealed, low temperature, gas reservoir that caps a much hotter liquid reservoir heated at depth by a magma chamber(s) fed by many years of intrusions. The gas in this semi-sealed chamber is 99% CO_2 and 1% N_2. Sustained low magnitude seismic activity breached this low permeability seal in 1989, leading to massive cold CO_2 exhalation along the pre-existing faults and fractures on and around Mammoth Mountain. This process is shown schematically in Figure 3. C and He isotopic ratios are consistent with a magmatic source for the CO_2 gas (Sorey et al., 1998), although additional CO_2 could also be produced from contact metamorphism of old Paleozoic carbonate-bearing roof pendants that crop out around Mammoth and presumably also at depth (Sorey et al., 1998). Recent work by Rogie et al. (2000) indicates that current CO_2 gas flux is > 95% magmatic in origin. Current estimates of whole-mountain CO_2 flux are 200-300 t/d (Sorey et al., 1999), while the flux at Horseshoe Lake alone is approximately 100 t/d (Rogie et al., 2000).

4.2.3 Local CO_2 flux at Horseshoe Lake

The Horseshoe Lake Tree-kill lies on the southern flank of Mammoth Mountain atop Quaternary andesites, dacites, and glacial tills. However, the subset of the kill analyzed in this study lies entirely on glacial till deposits. The dominant tree species in the Horseshoe Lake region is *Pinus contorta* (Lodgepole pine). Other species include *Abies magnifica* (Red Fir), *Tsuga mertensiana* (Mountain Hemlock), and *Pinus albicaulis* (Whitebark Pine). Initial measurement at this tree-kill by Farrar et al. (1994) led to estimates of 1200 tons/day of CO_2 diffusing from the ground from a single sample location. Present day multi-spatial, multi-temporal measurements indicate a reduced average flux rate of 100 tons/day (Rogie et al., 2000). The higher flux rates of 1994 are probably indicative of undersampling, and the recently reported lower rates are probably closer to the current flux state of the volcano. Though the CO_2 is fluxing diffusively from a large area around Horseshoe, its initial source is probably a fault or series of faults related to Bailey's Horseshoe Lake Fumarole Fault (HSLF on Figure 3-3) (Bailey, 1989). The CO_2 travels up along this fault(s) and diffuses into the soil when it reaches a certain depth. During the winter months, snow may behave as a dense soil layer, allowing the CO_2 to flux from areas of higher permeability in the snow, while trapping the CO_2 in other areas. Extensive studies of the temporal and spatial variability of CO_2 flux were done by Rogie and others since 1997 (Sorey et al., 1999; Rogie et al., 2000; 2001).

4.2.4 Vegetation and extreme levels of CO_2

Minor elevations of CO_2 can increase photosynthetic rates and aid in plant growth; however exhalation of CO_2 at the levels experienced daily on Mammoth asphyxiates most alpine plants and communities. Normal forest soil has CO_2 gas concentrations of less than 1%, but, the soils around Horseshoe Lake have CO_2 concentrations of 15-90% (Cook et al., 2001). Such concentrations deny tree roots access to oxygen leading to stomatal closing, which eventually inhibits tree respiration. Sustained high CO_2 flux leads to physiological weakening, and causes trees to become susceptible to other outside stressors such as drought, high elevation, nutrient deficiencies, and insect infestation. High flux can kill a community in a very short amount of time, but sustained lower fluxes may also become lethal over the long term.

4.3 Methods: Spectroscopic-based mapping of tree-kills

4.3.1 Previous tree-kill boundary mapping efforts

The tree-kill distributions on Mammoth Mountain were initially mapped using large-scale 1:14,500 aerial photographs taken in 1995 (Farrar et al., 1995; Sorey et al, 1998). The boundaries of a few specific kills were also surveyed using handheld GPS units, as well as two-color geodimeter measurements. Horseshoe Lake received early attention due to the massiveness of the kill and the large measured CO_2 flux: its boundary was measured twice using GPS, in 1994 (Farrar et al., 1995) and in 1998 (Rogie and Colvard, unpub. data, 1998). Such methods are time-intensive and limited by the subjectivity of human observers on the ground.

Two separate studies in the late 1990's used hyperspectral imaging to assess the boundaries of tree-kills on Mammoth Mountain. De Jong, (1996; 1998) had initial success at mapping tree mortality using 20 meter resolution AVIRIS data. De Jong also attempted to record the growth of the tree kills using multi-date AVIRIS scenes. While results were compelling, they were limited by registration issues and the narrow time steps studied. Hausback et al. (1998) used both AVIRIS and Thematic

Mapper Simulator (TMS-NS001) data. The spatial resolution of both data is approximately 20 m. Although the spectral resolution of AVIRIS was far superior (224 bands versus only 8 for the TMS-NS001), Hausback encountered several problems with both datasets due predominately to the coarse pixel size, the poor spectral resolution in the TMS-NS001 data, and the highly varied physiological state of the tree populations. He also attempted to discriminate spectrally among stressors or sources of tree-morbidity on the mountain (eg. differences between trees killed by CO_2 versus those killed by drought, insects, fire, flooding, etc.) with limited success.

4.3.2 Boundary discrimination using vegetation indices

The geometry of spectral signatures or spectra can be unique for certain materials. Minerals and many anthropogenic materials are easily identifiable from spectral libraries. Vegetation spectral signatures are more difficult. Signatures do not vary a great deal from species to species and hence vegetation spectral libraries tend to be site-specific and time-specific. The architecture of vegetation spectra is affected by a myriad of outside influences, including amount of sunlight, direction of sunlight, nutrient levels, water availability, temperature, etc. There are some inherent properties and characteristics of certain genera and species that can be detected. For example, the cutin on many conifer species needles will affect the way a spectral signature looks. Deciduous broadleaf trees don't have this cutin absorption. Within conifers, some species consistently appear a darker or lighter green than other species, and this difference is discernable and mappable in the visible wavelengths. The gross architecture of individual trees and whole stands can look different for different species. For example, Hemlock has long, upturned, alternate branching arms, while Lodgepole pine is tall and thin in stature leading to modified spectral characteristics. The overall structure of trees is generally detectable in spectroscopic data. Apart from these general characteristics of appearance however, vegetation is not easily spectrally identified by species.

Rather than seek unique spectra, researchers have turned to a robust, but blunt set of analyses termed vegetation indices or vegetation ratios. The concept is simple. The value of reflectance at a particular wavelength within one pixel is divided or ratioed with a value of reflectance at another wavelength within the same pixel. The resultant value is then assigned a color and ranked along side every other ratioed pixel within an image. Though simplistic, results from vegetation spectral ratioing techniques have proved to be quite powerful for many purposes and indices have become more sophisticated with time.

As an example, the NDVI (Normalized Difference Vegetation Index) takes the reflectance value in the infrared minus the red and ratios it with the reflectance value in the infrared plus the red. The intent behind this and other "red-edge" vegetation indices, is to capture the shallowing of the red-edge, or overall flattening of the plant spectral signature as the plant dies or loses greenness (i.e. chlorophyll) for any reason. Red-edge indicies reveal a broad characterization of overall greenness, which is often used as a proxy for vegetation health. One of my goals was to determine how successful vegetation indices would be for mapping tree-kill boundaries on Mammoth, and whether they discriminated between different sources of morbidity (e.g. CO_2 vs. fire).

Vegetation indices were calculated for a subset of HyMap data that covers the Horseshoe Lake Tree-kill region (Figure 3-1). The apparent reflectance data (Figure 3-5A) was subset to include only the first 54 bands (450 nm – 1236 nm) within the visible-near infrared wavelengths. Bare rock was masked out before ratio analysis by extracting bare rock signatures from the imagery for several rock types, then using them in a Spectral Angle Mapper (SAM) supervised classification to map areas of bare rock and soil. The resultant classifications were converted into a mask and applied to the data. Carter (1994) and Carter and Miller (1994) suggested that the ratios 695 nm/420 nm and 695 nm/760 nm are affected most strongly by plant physiological stress. Though their best results came from the 695 nm/420 nm calculation, this was not applied to the current HyMap data as the HyMap instrument doesn't measure wavelengths below 450 nm. Instead, the 695 nm/760 nm ratio was calculated. Because the spectral sampling (band width) of HyMap is larger than the handheld spectroradiometers that Carter and Miller used, I used band 17 (686 nm) and band 22 (762 nm) for the ratio analysis.

I also tested the viability of using the same 686 nm/762 nm ratio on a larger scene that encompassed several CO_2-induced tree-kills, as well as several other sources of morbidity. The Sotcher Lake scene, was used in this test and was much larger than the scene used to map the Horseshoe Lake tree-kill (Figure 3-1). It encompassed the central portion of Mammoth Mountain, including the summit region (see Figure 3-6A) and the Sotcher Lake area to the east. This scene covered elevations from 2100 m at Sotcher Lake to 3300 m at the summit of Mammoth Mountain. The scene contained areas of trees killed by several mechanisms including avalanche, fire, flooding, elevation effects, beetle infestation, and two CO_2-induced tree-kills (Figure 3-6A). The Sotcher Lake scene was spectrally subset and masked similarly to the Horseshoe Lake scene.

4.3.3 Boundary discrimination using MNF-derived endmembers

Though vegetation indices can be simple and effective, they leverage only a small portion of the available wavelength range inherent to hyperspectral data. Indices were originally designed for multispectral instruments with few bands: while multispectral satellites such as Landsat have only four bands covering the visible-near infrared (VNIR) portions of the electromagnetic spectrum, the HyMap instrument has 62 bands spanning the same VNIR portion of the spectrum. One way to exploit the complex spectral information inherent in hyperspectral datasets, is to calculate the principle components of each scene of interest. In general, principle component analyses suppress noise and enhance image signal. Individual signal images (principle component images) tend to represent broad material classes, and allow for simple, first order material classifications within an image.

The same image used for the vegetation indices (section 4.3.2), was used in the following principle components analysis. The data were subset to the first 62 bands of HyMap data spanning the visible through the near-infrared (450-1400nm). Then the Minimum Noise Fraction (MNF), a two-step cascaded principle components algorithm contained within ENVI©, was calculated for the scene. The first step "whitens" the noise in the data resulting in uncorrelated noise in every band and unit variance; the second step, a standard principal components transformation, results in a set of new n-dimensional axes (Green et al.,1988). The 20-22 MNF bands with the most signal and coherence, were retained and plotted as a correlation between the first two MNF bands. These two bands have the most signal and coherence, as well as contrast to each other (Figure 3-7).

4.3.4 Boundary discrimination using MNF-PPI derived endmembers and SAM

The method in section 4.3.3 is a quick way to survey spectral content of an image, but is a crude method for finding spectrally dominant materials or endmembers. Endmember thresholds were subjectively chosen from the MNF plots, and in only two dimensions. To determine endmembers in a less subjective and more quantitative way, a spatial reduction was run on the data. ENVI's Pixel Purity Index (PPI) algorithm finds the most spectrally pure (or extreme) pixels within a dataset. These purest pixels usually represent the dominant scene materials, and can be used to generate several different kinds of material classifications. In PPI, N-dimensional scatter plots of pixels are repeatedly projected onto a random unit vector and the extreme pixels falling at the end of the unit vector, are recorded for each projection. The total number of times each pixel is marked as extreme is calculated, and those pixels with the highest numbers are the purest (ENVI manual, AIG LLC, 1997). Only the purest pixels are used in the next step: this spatially reduced the dataset greatly. The Horseshoe Lake MNF images had approximately 67,500 pixels, which the PPI algorithm reduced to around 1000 pixels which retain both their geographic locations and full spectral information within the original image. These pixels were then projected into n-dimensional space within the N-Dimensional Visualizer of ENVI© which allows the user to visualize hyperspectral data in its full dimensionality. In the case of the Horseshoe Lake scene, the data was viewed in all 22 MNF dimensions. The most extreme points in one or more dimensions were delineated as endmembers from this 22-dimension plot and exported as 122 band spectral signatures into a spectral endmember library. The spectra represented a complex mix between species type, physiological state, and background rock/regolith.

The endmember spectra were used in Spectral Angle Mapper (SAM), a classification algorithm that determines the spectral similarity between two spectra. Spectra are treated as vectors in n-dimensional space with n equal to the number of bands being used. The angle between the unknown and known spectra is calculated, compared, and determined to be a match or not. This calculation was done for every pixel, resulting in a SAM classification map consisting only of pixels assigned to one the endmembers within the spectral library.

Several questions were then considered. Can tree-kill endmember spectra extracted from one HyMap scene be used as inputs for SAM classifications of tree kills in a separate scene? Specifically, would spectral signatures of CO_2-induced dead trees extracted from the Horseshoe Lake scene accurately map CO_2-induced dead trees in a SAM classification of the Sotcher Lake scene? Was there something unique to spectral signatures of trees killed by CO_2 vs. trees killed by other means, and if so, was it detectable across scene boundaries? To answer these questions, the spectral endmembers extracted from the Horseshoe Lake line were used as inputs for a SAM classification of the Sotcher Lake line. In both classifications, water and rock masks were applied before SAM processing commenced.

4.3.5 Boundary discrimination using MNF-PPI derived endmembers: MF

For the Matched Filter (MF) algorithm, spectral endmembers are extracted in the same fashion as for the SAM analysis, then entered into a MF algorithm which determines the abundances of those endmembers using partial unmixing routines. Endmembers within a scene do not need to be known. Classification results produce an individual rule abundance image for each endmember instead of the single classification map that the SAM generates. The rule abundance images were reduced by applying a threshold to the values in each individual endmember class image to retain only those pixels with the best matches to the given spectral signatures from the endmember library. The threshold values were then assigned a rainbow scale correlating to the goodness of fit to the original endmember spectra, (the best matches were in red, and the worst in purple/blue; no match is assigned black).

4.4 Results

4.4.1 Boundary discrimination using vegetation indices

The 686 nm/ 762 nm ratio provided an excellent spatial agreement with previously mapped tree-kills (Figure 3-5B). shows the 686 nm/762 nm ratio analysis. In these pixels, the red-edge of the spectrum is flattened, indicating that vegetation in these areas is dead or dying. Yellow to green pixels contain vegetation spectra that are also spectrally flattened, but less so than red pixels. Blue pixels possess somewhat flattened spectra, but these trees are only mildly physiologically stressed. They show small signs of weakness such as mild chlorosis of their needles, but many are probably perfectly healthy. Dark blue to purple pixels are probably healthy trees. Two major kill zones were mapped, Horseshoe Lake and the Borrow Pit (Figure 3-5B), with a secondary region of kill in the northern corner of the image. The Horseshoe Lake Fumarole (HSLF) kill was more poorly mapped.

Results of the 686 nm/ 762 nm ratio in the Sotcher Lake scene are shown in Figure 3-6B, where the same rainbow color scale is used as that for the Horseshoe Lake scene. The rock mask for this scene was less successful than for the

Horseshoe Lake scene, and several areas on the summit mapping as high stress values have no known vegetation and are clearly false positives. Another false positive is a region in the north central part of the image (labeled Hem. on Figure 3-7B). Mineral mapping indicate that this region is predominately the iron oxide, hematite whose spectrum in visible wavelengths, loosely resembles unhealthy vegetation, hence its high ratio. Actual vegetation mapped as having high ratios and hence depressed physiological states are indicated on Figure 3-7B. These include areas of sparse vegetation, avalanche zones, fire kills, and CO_2-induced kills.

4.4.2 Boundary discrimination using MNF derived endmembers

Figure 3-8A shows MNF Band 1 (x-axis) plotted against MNF Band 2 (y-axis). The spread of points represents the major spectral populations of materials including not only trees, but also water, rock and altered rock. By analyzing the correlation of Band 1 and Band 2 within the spectral tree population, we discriminated three important classes of tree physiological condition with the spectral signatures in Figure 3-7B. These spectral signatures are used to create an automated classification (Figure 3-7C).

The MNF Band 1 to 2 correlation allows discrimination of populations of trees based on their relative physiological state. The loss of chlorophyll absorption in the red wavelengths is readily seen in the conifer population spectral plot (Figure 3-7B). The progression from robust populations (1) at the bottom of the MNF band correlation plot (Fig. 3-7A) to populations at an intermediate physiological state (2) is matched spectrally by a loss in the chlorophyll absorption as well as an overall decrease in near-infrared reflectance (Fig. 3-7B). Population 3 illustrates the least healthy vegetation in the image. Figure 3-7C shows those zones with fairly high densities of unhealthy or stressed trees outlined in blue. Most of these zones correlate to known areas of CO_2-induced tree-kill.

4.4.3 Boundary discrimination using MNF-PPI derived endmembers and SAM

Figure 3-8A shows the spectral signatures of endmembers extracted from MNF-PPI analysis. The full spectral range is shown because all 122 bands were used in the classification effort. Figure 3-8B is the resultant georectified SAM classification. The patterns of the main tree-kills look similar to patterns produced by indices and MNF analysis, with the blue colors indicating regions with a high kill rate. These spectra illustrate loss in the chlorophyll absorption in the red wavelengths, a flattening of the near-infrared plateau, and pronounced lignin and cellulose absorptions around 2.10 μm and 2.25 μm, indicating a high amount of bark and less foliage within each pixel. The red, orange, green, and turquoise colors represent healthy, robust tree populations with high absorptions in the red wavelengths, high near-infrared plateau reflectances, and very little absorption in the SWIR due to cellulose and lignin. The lavender class is unusual: geometry of its spectral signature indicates an intermediate degree of health, and these trees are distributed around the edge of the main kill. Again, speckled positive results for stressed and/or dead trees is seen throughout the image, but especially in that area between the main kill and the HSLF kill.

Figure 3-9A shows the endmembers extracted from the Sotcher scene using the MNF-PPI method. All 122 reflectance bands are shown. A little more than half the signatures have deep absorptions in the red wavelengths, corresponding to high levels of chlorophyll and indicating healthy plants. Four signatures have a loss in absorption in the red wavelengths, indicating less greenness and thereby chlorophyll.

The light green, red, and blue signatures have markedly decreased reflectance in the NIR in addition to reduced red absorption. Figure 3-9B is the georectified resultant SAM classification using Sotcher scene endmembers. Major zones of kill are indicated where an association of red, light green, blue, and yellow pixels is fairly prevalent. Dense clustering of magenta plus blue and cyan plus green are also observed throughout the line. No signal is apparent in the known CO_2 kill area.

Figure 3-10B shows the results of using Horseshoe Lake endmembers to map tree-kills in the Sotcher Lake line. The colors are the same as in Figure 3-8A, with one exception: the dark blue of HSLF kill population (Figure 3-8A) was changed to magenta (Figure 3-10B) to visualize this classification better. There is a widespread association of blue with magenta, as well as large areas of green and red. The areas of known CO_2 kill are classified as dead trees; however large areas of healthy trees are also classified as dead. Zones of known avalanche and fire kill are classified as green.

4.4.4 Boundary discrimination using MNF-PPI derived endmembers and MF

The physiologically stressed tree (Figure 3-8A) were used in a MF classification. The results are illustrated by the image for one of the high kill signatures (Figure 3-11B). Initially these MF results do not seem to match the known tree-kill boundary as well as the previous methods, but the MF results actually appear to correspond to those regions probably undergoing the highest levels of stress due to anomalous CO_2 flux. Figure 3-11C shows the CO_2 efflux as measured by Rogie and others in 1999 (Sorey et al., 1999). The zone marked 1 on Figure 3-11B and 3-11C corresponds to a region that has the most stressed trees and very high CO_2 flux; the area marked 2 in Figure 3-11C has the highest flux at Horseshoe Lake, but shows no corresponding zone of stressed trees in Figure 3-11B.

4.5 Discussion

4.5.1 Vegetation Indices

The 686 nm/762 nm ratio analysis of the HyMap data for the Horseshoe Lake scene was successful for detecting dead trees. The boundary of the known tree-kill matched the boundary of the kill determined from the ratio. However, the area analyzed was limited and spectral variability within the scene was minimal. The major source of morbidity was CO_2 flux, and there were no other major sources of morbidity known within this scene. There are areas with less convincing delineations of tree kill such as the HSLF area where the speckled distribution of high ratio pixels around the HSLF and to the east (Figure 3-5B) suggest the presence of false positives generated from mixing of substrates within pixels.

The average elevation of this scene is approximately 2740 m, which results in a HyMap pixel size of approximately 3.5 m. Though this spatial resolution is quite fine compared to most remote sensing instruments currently flying, it still allows significant mixing of materials within pixels. Figure 3-12 illustrates effects of mixing with several synthetic spectral signatures for varying percentages of rock and vegetation within one synthetic pixel. Even small percentages of rock within a pixel tend to flatten the red-edge and mimic physiological stress; and only 25% rock could act as a false positive for plant morbidity. Rock-masks attempt to remove pixels with moderate to large percentages of rock from analysis. Such masks are not quantitatively determined. The cutoff value for treating a pixel as tree or rock is determined qualitatively and empirically on a scene-by-scene basis, and masks are usually less conservative, i.e. it is likely that there will remain pixels containing appreciable amounts of rock material.

The Sotcher scene CO_2-induced tree-kills were effectively mapped using the ratio method, but kills due to other sources, such as avalanche and fire, were also detected and mapped similarly to the CO_2 kills. The regions of kill due to avalanche were especially well delineated with the ratio method. Most importantly, the CO_2 kills and avalanche/fire kills were not discernable from one another, since, like CO_2 kills, fire and avalanche kill areas have large amounts of dead trees, bare soil, and regenerative low-lying vegetation. The mixing of these endmembers produces a signature similar to physiological stress. Similarly, areas with small percentages of trees and large percentages of rock also mimic physiologically stressed vegetation. Essentially, all of these stressors generate landscapes with similar spectral signatures. In addition, all dying trees lose chlorophyll, which results in the flattening of the red-edge. As the red-edge flattens, values of ratios will increase, no matter what caused the loss of the chlorophyll.

4.5.2 MNF-derived endmembers

The MNF transform produced a fairly accurate map of the main CO_2 tree-kills at Horseshoe Lake. The southern area labeled “robust” is known from fieldwork to be a thick, healthy, mixed species conifer forest with no signs of physiological stress or CO_2 weakening. Conversely, regions mapped as physiologically stressed (e.g. population 3 in Figure 3-7A,B) have probably lost chlorophyll due to anomalously high levels of soil-CO_2 (outlined with a blue line in Figure 3-7C). However, many other factors can lead to loss of chlorophyll. In this region, sickness due to beetle infestations has been observed and drought and heat can cause a loss of chlorophyll. In short, most conditions adversely affecting a plant's metabolic system can lead to a loss of chlorophyll. Independent knowledge is therefore required to narrow the sources of morbidity in vegetation. This knowledge is readily available at Mammoth Mountain, unlike more remote volcanoes that usually lack primary monitoring data.

The western region labeled "diffuse kill" (Figure 3-7C) is hard to interpret. This region is not known to have elevated levels of CO_2, but the spectral signatures indicate a substantial among the predominate lodgepole and limber pines. The speckled distribution of both stressed and non-stressed vegetation between the HSLF and the HSL kill is still evident, and may reflect mixing effects such as those in Figure 3-12. However, investigation of the longer wavelengths (2.0-2.5 μm region) of these physiological spectral classes indicated little evidence of mixing. Most signatures displayed characteristic vegetation absorptions in this region, although some populations (such as 3) may have some mixing, especially near that part of the MNF plot exemplifying clay and sand. Alternatively, these flattened, low-chlorophyll signatures may be real. This section of forest is less dense than the "robust" forest to the south. It is likely that repeated degassing events in this locale over millennia has led to acidification of the soil, making life at these high elevation, nutrient deprived ecosystems even more difficult (McGee and Gerlach, 1998). This acidification may have caused long-term thinning of the lodgepole forest and chronic nutrient deprivation inducing perpetual physiological stress for these trees, decreased chlorophyll production, and hence lowered chlorophyll absorption in the red wavelengths. Further implications and the mechanisms behind the soil acidification are addressed more fully in section 5.4.

4.5.3 SAM analysis

The SAM classification (Figure 3-8B) produced an accurate map of the known tree-kill distribution. It also produced a new class not seen in previous analyses. The signature designated as Halo Populations was restricted to the edges of the Main and Borrow Pit kill; it was particularly dense to the southwest of the main Horseshoe Lake kill (Figure 3-8B). The halo spectrum is intermediate between the higher kill % signatures and the robust population signatures. Field work in this region reveals that the living trees have obvious signs of stress, including chlorosis of needles and stunted growth of juveniles, and there are dead trees spread out sparsely within the area. These areas are probably zones with sub-lethal levels of CO_2 and/or other stressor, where the trees are physiologically weakened by one or a combination of stressors, and are slowly dying. Scattered pixels of this lavender class elsewhere in the image may be due to pixel mixing.

The SAM classifications of the Sotcher scene are more complex, partly due to the larger size of the dataset and its subsequent increased spectral variability. The extracted endmembers appear to capture combinations of vegetation physiological state, general community/species type and background soil/rock. Regions north of Sotcher Lake that are colored in cyan, green, and some yellow appear to be healthy, dense forest. During field work, the trees were mostly red fir and lodgepole pine. The scattered red pixels over the summit area probably are not stressed trees. While extreme elevations can cause physiological stress, the apparent stress signatures are probably a function of mixing rock and tree signatures. The dense clusters of magenta are mainly grasses, especially along the Twin Lakes and the Horseshoe Lake roads, while the magenta regions south of

Sotcher Lake are also grass-filled meadows. Magenta in known avalanche and fire kill is also probably grass, since regenerative vegetation is dominated by grass and low growing shrubs. The red and green classes come closest to mapping areas of known dead trees, including the avalanche, fire, and mysterious kills along the Horseshoe Lake road. Other red areas east of Twin Lakes and along the road are due to rock mask failure. In this SAM analysis, the CO_2-induced kills are not detected very well, at least with the current set of endmembers. New endmembers extracted straight from the CO_2-kill areas and applied in a modified SAM classification would probably increase the accuracy of detecting and mapping of CO_2 kills.

In the last part of the SAM analysis, Horseshoe Lake endmembers were applied to the Sotcher Lake scene (Figure 3-10B). There appears to be less variation, but this is due to fewer endmembers being used in the classification. The Horseshoe Lake high % kill endmembers detected the fire and CO_2 kills, but also mapped many other areas, including many on the western and far eastern flanks. Some of the known grassy areas are mapped successfully (in green), but much of the forest on the eastern flank is also mapped as grass. This confusion probably reflects too few endmembers to fully characterize the scene variation. This is one reason why it is better to extract endmembers on a scene by scene basis, rather than using a general vegetation library. The variability of vegetation and its gross spectral similarity of most plant spectra, demand individual scene spectral extraction. The halo signature only occurred in a few locales on the western flank, where it appears to be a new kill zone that has not yet been mapped. However, recent CO_2 detection work presented in Chapter 4, indicates that this spot may be a zone of CO_2

flux. This kill is known to exist from personal communications with local Mammoth geologists, and the SAM classification may be finding weakened dead trees due to recent CO_2 exposure.

The fact that the Horseshoe Lake endmembers provided a better map of CO_2-induced and other kills suggests that the Sotcher Lake scene used in the SAM classification of Figure 3-9B and 3-10A is too big. The spectral variability was too great to detect spatially restricted signatures such as dead trees in the vicinity of anomalous CO_2 fluxes. In conclusion, extracted endmembers are most useful when their identity is conclusively known from field examination and not simply inferred from “unhealthy” signatures.

4.5.4 MF analysis

The results of the MF analysis, while apparently accurate, are poorly constrained. The pattern based on the high % kill endmember is strikingly similar to the flux pattern described by daily flux measurements (Rogie et al., 1999), while this correlation suggests that zones of high CO_2 flux may be detectable remotely, via geobotanical response characterization. Two major problems need to be considered. First, the high flux site 2 was not detected by the MF analysis (Figure 3-11B,C), due to the lack of trees: after the trees died in 1990-1991, the U.S. Forest Service cut many of them down, leaving only stumps and bare ground. With no vegetation in which to measure a geobotanical response, there was no signal to be detected in the MF analysis. This suggests that CO_2 areas above tree-line, or on other regions of bare ground, would not be detected by such an analysis. Many volcanoes that flux gases similar to Mammoth, do so above tree-line. This technique may thus miss many flux spots if used on other volcanoes. Second, although we see a higher degree of stress in areas of higher flux, there is no current method to quantify flux using only hyperspectral data. Field data are still absolutely necessary. At best, this technique may provide a rough first look at those vegetation zones more stressed than other zones. Whether these zones of stress correspond to gas, heat, drought, or extreme chemistry requires further ancillary field and monitoring data.

5.0 A temporal analysis of Horseshoe Lake tree-kill growth since 1989

5.1 Introduction: Timeline of tree-kill growth; unanswered questions

Tree-kills were first noticed in 1991 at several locations around Mammoth Mountain including Horseshoe Lake on the southern flank and Chair 12 and Reds Lake on the northern flank. Several other kills appeared in the years following 1991, including Reds Creek on the western flank and several kills on the north face of the mountain in-bounds of the resort. Cook et al. (2001) determined through radiocarbon measurements at the Horseshoe Lake kill that almost all the trees sampled there began fixing less carbon-14 beginning in 1990. This deficiency in carbon-14, characteristic of magmatic CO_2, was also measured in trees at Reds Creek. Cook et al., (2001) indicates that peak flux occurred in 1991, decreased steadily from 1991 to 1995, and then was fairly constant till 1998. In addition, measurements of trees near cold CO_2-rich springs on the flanks of Mammoth indicate that degassing via groundwater has occurred (in at least one tree) since 1967. This is some of the only quantitative knowledge we have about how the tree-kills have grown through the years. We don't know how the tree-kills grew, as none of their boundaries were actually surveyed until 1995. Knowledge of the initial sites of death and the subsequent trajectory of growth of the kill zone boundaries is likely to reveal information about subsurface structure system and pathways of CO_2 propagation. I analyzed multi-temporal airborne remote sensing data to determine a semi-quantitative measure of the growth of the tree-kill at Horseshoe Lake. It elucidates how the kill at Horseshoe Lake began, how it grew, and its current trajectory.

5.2 Methods: Historical air photo analysis

Numerous air photo exist due to interest in volcanic activity in this region of California. Because air photo registration and analysis is time-consuming, not all available years of air photo were analyzed in this study. Instead, air photo of differing scales and seasonal character were selected and analyzed for the years 1977, 1990, 1993, 1994 and 1995 (Figure 3-13), and a 1999 hyperspectral HyMap image was also included in this analysis. Each photograph was scanned in at 800dpi and saved as a TIFF. The photos were subset to include the Horseshoe Lake tree-kill and 1-2 km of area surrounding the lake. The approximate location of these photos and hyperspectral image is shown by the red rectangle in Figure 1.

Several different methods were used to determine the boundaries of the kills in each photo. Because these photos only contain three color bands (1993 only contains one panchromatic band), spectrum-basede was not possible. Based on the principles discussed in section 4.3.2 concerning vegetation indices and the geometry of plant spectral signatures, dead or dying vegetation appears less red in near-infrared photography. Enhancement techniques such as linear and gaussian stretching, were used for detecting and delineating kill boundaries; all the color photos were actually color-infrared, spanning not only standard visible wavelengths, but also some energy in the infrared portion of the spectrum, and more sophisticated methods such as MNF transforms applied to the digitized images enhanced the results. Resultant tree-kill boundaries were hand-digitized into regions of interest (ROIs) and exported as separate vectors. The area of each vector polygon was calculated in hectares (inset table of Figure 3-14). Figure 3-14 also shows the vectors from all five years including the vector from the 1999 HyMap data which was derived by methods in section 4.3.4. Horseshoe Lake is placed at the bottom for reference. Each photo was georectified using 30-50 ground control points. RMS errors were generally < 1 to ~ 2, and were never > 7. Visual comparison of images with one another suggest that georectification was consistently very good.

5.3 The growth of the Horseshoe Lake tree-kill: Results

5.3.1 New temporal and spatial patterns revealed

The georectification and resolution of the photographs are sufficiently good to provide a fairly consistent picture through time of the growth of the Horseshoe Lake tree-kill. Minor discrepancies in boundary delineations are likely due to georectification and operator digitization errors. Some excursions mapped are probably due to the increased measureability of dead trees and sub-morbid populations (the so-called “halo zones” of the tree-kill) using hyperspectral data. However the major boundary excursions, such as that between 1993 and 1994, are probably real and are unlikely to be due to analysis error.

Boundary delineation using the MNF was successful; it added little to the simple stretching techniques. The most difficult image was the 1993 panchromatic photo. While the tree-kill is visible in this photo, it doesn’t stand out as well as it does in the color-infrared photographs (Figure 3-13). Stretching routines also didn’t work as well with this photo, and the single panchromatic band makes an MNF analysis impossible. Accordingly, boundary delineation in 1993 is the least reliable, and to be conservative, the boundary contains less detail (blue line of Figure 3-14). The 1994 boundary is also a bit blocky and rough due to the relatively poor resolution of this photo (scale of 1:55,600).

In 1990, the tree-kill was approximately 4.5 ha including the beginnings of the northern Borrow Pit kill which was previously reported to have appeared later (in 1993) (Cook et al., 2001). From 1990 to 1993, the main kill remained about the same size, but the Borrow Pit kill continued to grow and a new satellite kill appeared to the south of the main kill. From 1993 to 1994, the tree-kill at Horseshoe Lake more than doubled in size from approximately 5.1 ha to 11 ha. This expansion has not previously been reported. Because Cook et al. (2001) does not indicate any increase in degassing during this time period, the expansion may represent a time lag in expression of effects of the initial pulse of CO_2 degassing at Horseshoe Lake. Cook et al. (2001) concluded that trees towards the center of the kill experienced the CO_2 pulse first and died fastest. This is supported by the present analysis that shows the initial kill in 1990 near the center of the current kill zone (see Figure 3-15). Trees at the center of the CO_2 flux zone probably died immediately. Plants under stress will often, among other defenses, laterally spread their roots to avoid stressors of different kinds. The Horseshoe lake trees in the center of the kill zone would not have had time to do this. Transpiration and mineral and water uptake would have ceased. Airborne CO_2 at the levels seen in the kill during this initial time period (1200 tons/day (Farrar et al., 1995)) probably led to the widening of stomata in the conifer needles to accept more CO_2 (which plants normally like) (Larcher, 1995).

However, the continued flux of CO_2 at these levels led to the closing of the stomata completely in order to ward off the increasingly noxious levels. Very quickly, the trees would have ceased respiration and photosynthesis. They were effectively suffocated. Cells cease to function and the trees died.

Trees further from the main CO_2 source zone, might not have received a lethal initial CO_2 pulse, but probably received enough to cause physiological stress. Chronic flux continued to weaken these more peripheral trees until many of them finally died after the particularly severe winter of 1993-1994. It is well known that a combination of stressors on an ecosystem is more lethal than merely one stressor. The heavy snows and late spring served to exacerbate the CO_2 problem. In addition, Cook et al. (2001) found that peripheral trees tended to die approximately four years after initial deficiencies in carbon-14 were measured. The above scenario would explain why the tree-kill is not growing rapidly at present. Continuing flux from a fixed point source would keep the dead tree areas devoid of life, and border trees in a state of heightened physiological stress. Other stressors such as drought or insect infestation may lead to a new kill, but without an increased flux rate or new locations of flux, the kill will likely remain constant in size. New zones of kill therefore, may or may not be due to increases in flux and hence new kills should be surveyed not only for CO_2 flux, but also for other external stress sources.

The above analysis could easily be done for other regions of Mammoth. Cook et al. completed radiogenic measurements on trees from Reds Creek that indicated CO_2 flux was occurring in this region at least since 1967. Multi-temporal air photo analysis would reveal exactly when other trees began to die at Reds Creek historically, as well as when trees began to die around the mountain after the 1989 seismic event. Any correlations between timing of individual kills may indicate similar sources at depth or a subsurface connection. Aerial photography doesn't exist for this region before the late 1970's, but twenty years would be a good start.

5.3.2 Discussion and conclusions: Paleo-kills and de-fertilization of soils

The history of these tree-kills is longer than that capable of being recorded by aerial photography. Tree-coring suggests that the previous kill in the HSL area was approximately 250 years ago. While there is no direct evidence that this paleo-kill was due to CO_2 , geochemical evidence suggests that acid-loading of the soils from carbonic acid derived from high soil CO_2 gas percentages may have been going on at the Horseshoe Lake site for millennia (Mc Gee and Gerlach, 1998). Chemical weathering rates are low in the high Sierra, hence buffering of acid by silicate weathering is not a dominant process (Taskey, 1995). The soils at Horseshoe lake are very immature and McGee and Gerlach suggest that acid buffering is accomplished with cation exchange that leads to increased H^+ loading from the dissociation of the carbonic acid (H_2CO_3) and nutrient deprivation of the soils. Starting pHs for soils at Horseshoe Lake are approximately 5.5, but continued acid loading in the kill zones has brought the pH down to 4.0. At this level, clays begin to break down, releasing Al^{3+} into the system. Al^{3+} binds with carbonate, causing Al toxicity in the soil and continued release of H^+. Even if the soils had only 50% CO_2 , this level of flux would lead to some of the highest acid-loading reported world-wide (Mc Gee and Gerlach, 1998). Soil CO_2 gas percentages in the Horseshoe Lake region often approach 90%. This region is highly susceptible to acid loading of the soils and hence this nutrient poor, high elevation ecosystem becomes even more of a challenge to vegetation communities.

A common vegetation response to nutrient poor soils is decreased density of growth. Figure 3-17 compares the 1977 aerial photo (left) with the 1990 tree kill boundary superimposed on it (right). The boundary of low density, but healthy trees in 1977 was very similar to the boundary of dead trees in 1990. This suggests the area of low density trees has been the main source of CO_2 for many years. Many cycles of carbonic acid loading derived from individual volcanogenic CO_2 degassing events may have contributed to decreased fertility in this region. The few trees that do grow (Lodgepole pine) are quick-growing trees accustomed to opportunistic growth in recently disturbed regions.

6.0 Tracking abnormal grass phenology in fumarolic enviornments

6.0 Introduction

The remote sensing techniques presented thus far have leveraged localized plant spectral responses to volcanological activity. While community responses to massive exhalation of CO_2 were mapped in space and time, such exhalations are rare in geothermal environments. Other phenomena are much more widespread. One of these is elevated ground temperature, which is universally found within geothermal environments, and that also has spectrally detectable effects on vegetation. The following study used a hand-held spectroradiometer in a field project that documented spectral signatures of vegetation within a fumarolic field in the central caldera near the Casa Diablo Power Plant. An association between changing spectral geometries and soil temperature was expressed as a striking vegetation zonation pattern.

6.2 Background: Casa Diablo Horst Fumaroles

Increased soil temperatures are common in many places around Long Valley Caldera. High heat flow is commonest along structural weaknesses, including faults, fractures, and contacts. Heat is usually conducted via hydrothermal fluid flow, which appears at the surface as either a liquid, in the form of creeks, hot pools, springs, or as a gas (e.g. steam from fumaroles). A fumarolic zone with a visible zonation pattern lies near the Casa Diablo geothermal plant in the western-central caldera (Figure 3-1). The fumaroles are approximately 0.5 km from the main injection and extraction wells of Casa Diablo where two small north-trending normal faults cut the crust (Figure 3-16A). Displacement on these faults has produced a small horst with down-dropped grabens on either side. Several fumaroles are aligned along both the western and eastern faults. Ground temperatures on top of the horst are not much above normal soil temperatures (20-30 °C), however soil temperatures at 30 cm depth near the fumaroles approach 78°C.

The horst itself is covered in Jeffrey and Pinyon Pine, sagebrush, antelope bush and grasses. The steam travels up the small normal faults and appears to use the tree-roots as preferred conduits of transport nearer to the surface. The temperatures decrease with distance away from the fumaroles, eventually leading to the death of the trees and surrounding vegetation. Tree and shrub communities away from the faults and fumaroles on top of the horst remain unaffected and show no signs of morbidity or death. Figure 3-16B shows the field site with the tree-kill zones delineated.

6.3 Methods: Field spectroscopy

The more vigorous eastern-fault fumarolic region was chosen for spectroscopic measurement due to its obvious vegetation zonation pattern. A transect perpendicular to the fault was set up. The transect began downslope from the fumaroles in healthy-looking grass and shrub community and stretched uphill through the grass and ended at a fumarole in bare ground (dashed magenta line, Figure 3-17A). Spectroscopic measurements were acquired approximately every meter with a handheld GER 1500 consisting of 512 channels measuring 300 nm to 1100 nm. All spectroscopic measurements were taken of annual grasses at approximately 11:30 AM Pacific Standard Time on May 29, 1999. A reference measurement from a standard spectralon plate was made before each radiance measurement. The radiometer was held approximately 50-60 cm above the ground to capture a significant amount of grass in each trial. Each radiance measurement consisted of five consecutive spectra that were automatically averaged into one signature/measurement. When divided by the reference spectra the radiances were expressed as reflectance signatures. At each station, soil temperature was measured at a depth of 30 cm using an analog temperature probe pushed into the ground.

6.4 Results

Soil temperature zones are superimposed on Figure 3-17A, while representative spectra of grasses from different regions of the transect are shown in Figure 3-17A. The gradient from the region supporting healthy grass to the zone of lethal soil temperatures was short, only 5-10 meters. Within this gradient, the vegetation was zoned conspicuously with increasingly senesced grass populations towards the fumarole, is readily seen in the photograph of Figure 3-17A. The five spectral signatures representing the different temperature regions at Casa Diablo Horst are noticeably different from one another. The greener populations at the beginning of the transect retain a deep chlorophyll absorption at 690 nm and flattened near-infrared plateau. There are only minor differences between the spectra taken at 77°F (25°C) ground versus 80°F (27°C) ground. The 92°F (33°C) grass community spectra begins to show the effects of increased heat with a reduced chlorophyll absorption and a steepening of the near-infrared plateau. Spectra taken of grass on ground with 99°F (37°C) and 108°F (42°C) temperatures have completely lost any chlorophyll absorption and have severe shallowing of the red-edge and steepening of the near-infrared plateau. There is a definite decrease in the chlorophyll absorption in the red wavelengths with increasing soil temperature. A spectra for 182°F (83°C) ground is not shown, as there was no grass, dead or alive, on the soils with these high temperatures.

6.5 Discussion and Conclusions

I suggest that the increased ground temperatures due to geothermal heating has increased the phenological cycle for these grass communities. Grasses nearer to the fumarole are essentially experiencing an accelerated senescence at rates faster than normal. Degree days (cumulative heat above developmental threshold) is of utmost importance in phenological cycles of vegetation. Usually, increases in ground and air temperatures in the early spring that begin the life cycle of annual plants after their cardinal temperatures of germination are reached. The germination rate increases exponentially with rising temperatures (Larcher, 1995). Generally, the optimal temperature for germination of grass seeds is about 20°C. The maximum temperature is approximately 30°C. After germination, seedlings take root. The seedling stage is the decisive life phase for plants. If seedlings don't thrive, the population will not spread. Seedlings are highly susceptible to various stressors, including drought, lack of nutrients, and excessive heat. If the seedlings are able to take root, the main phase of growth begins and peak metabolic activity is enjoyed by the plant (photosynthesis, respiration, and uptake of minerals). It is in this phase that plants are most resistant to stressors and capable of stress hardening and a certain level of regeneration after a stress period. This phase is followed by the reproductive phase and generation of seeds in which temperature again plays a very important role. Under chronic stress (such as excessive heat), very few seeds are produced in most plants and germination of these is poor. Chloroplasts lose their proteins and pigments. The plant becomes more susceptible to abiotic stress. Eventually, death of the organism occurs.

The grass-sagebrush-pine communities are approaching their peak greenness due to expansion of new young leaves at this elevation (~2300m) in late May. The grasses would have germinated, seedlings would have taken root, and the leaves would be in their main phase of growth. The pines and sagebrush would have left dormancy and would also be enjoying peak metabolic activity. The grasses near the fumaroles however, were well into their senescent phases as of May 29th. They were completely red, having lost their chlorophyll. Closest to the fumaroles, the grasses were quite dead. The trees and shrubs were also dead near to the fumaroles. In fact, the grasses actually survived closer spatially to the fumaroles than the other vegetation. The heat injury threshold in herbaceous species of sunny habitats is approximately 47-52 °C while grasses may have higher thresholds from 60-65 °C (Larcher, 1995). Grasses and sedges are especially heat tolerant. Initial inception of heating probably shocked the resident vegetation in this region, causing permanent cell structure and cell function damage. The chloroplasts were damaged, photosynthesis was depressed, and the cell died. With time, it is likely that the increased temperatures accelerated the rate of germination of grasses farther from the fumaroles. This lead to early development and fast rates of growth. Those seedlings trying to take root too near to the fumaroles would not survive the excessive temperatures. Seedlings taking root within the slightly elevated temperature regions would have increased rates of growth. The chronic source of heat also allows for rapid reproduction and seed production. As mentioned previously, grasses in this high heat environment likely produce few seeds. However, once the few seeds have dropped, senescence takes hold and the grasses turn red and die. Though not well-constrained, the life cycle of grasses at Casa Diablo are shortened from approximately three months to one month due primarily to geothermal heating.

These initial spectroscopic field studies at the Casa Diablo Horst indicate that regions of increased ground temperature may be discernable from hyperspectral airborne data. The physiological and corresponding spectral changes would likely be measureable in hyperspectral imagery, given a high enough spatial resolution that captures the scale of the zonation pattern. In the Casa Diablo case, 1meter data would probably capture these patterns. In addition, imagery would need to be acquired in the spring when the grasses are entering their peak growing phase and their accelerated geothermally induced senescent phase. If the data were acquired in the late spring or summer, such zonation patterns would be absent, as the grasses would all be dead. The HyMap data currently in hand for this region has a spatial resolution of approximately 5 m at the Casa Diablo elevations and was taken on September 7, 1999, hence it is inappropriate for this analysis. In conclusion, future hyperspectral airborne images taken in the early spring would probably reveal zones of ground with elevated temperatures by simply mapping the degree and patterns of grass senescence and tree death and morbidity. Such techniques could lead to new ways of characterizing geothermal regions and their discharge zones.

7.0 Detection of vegetation zonation patterns at hot springs and pools

7.1 Introduction

The compositions, spatial distribution, and density of vegetation are controlled dominantly by regional climate and elevation, and secondarily by local climatic variables and substrates upon which the communities grow. Volcanic environments impose additional, geologic forcings on plant communities; primarily elevated ground, water and air temperatures, anomalous levels of noxious gasses, tectonic movements, and outright eruptions of volcanic materials. Thus, geothermal districts traditionally host biologically diverse ecosystems in and around their thermal features such as fumaroles, hot springs, creeks, and pools. The fact that these communities are different from regional vegetation distributions, makes them important indicators of the volcanic activity itself. Furthermore, many plants and microorganisms such as bacteria and algae, subsist in fairly narrow life zones bounded tightly by temperature, pH, salinity, etc. thresholds. Mapping volcanic-hosted biological communities thus pinpoints and grossly characterizes volcanic environments.

Very few earth environments are devoid of biological material. While semi-arid Long Valley Caldera in the eastern Sierra Nevada of California is sparsely vegetated with predominately steppe-like shrub communities and thin, sub-alpine conifer forests, many other geothermal regions around the world are covered in thick jungles and lush grasslands. Vegetation is not only difficult to remove from most volcanic areas of interest, but remote sensing-driven mapping and analysis of biological communities is one way to characterize a geothermal region for resource potential and/or general understanding of a particular volcanic system. Rather than attempting to remove biological signals from remote sensing data, I suggest a more holistic, geobotanical approach towards image analysis, in which the biological information is left in place within the imagery data.

The previous study of elevated soil temperature and grass phenology (section 6.0) is one example of the geobotanical approach towards volcanic characterization. The following study extends that example by investigating patterns of vegetation around hot springs and pools, and evaluating our abilities to map these communities remotely. Microorganisms within these thermal waters were also measured and analyzed. Several types and qualities of hyperspectral data are used in this study, leading to recommendations about the best and most efficient instrumentation to use for such a geobotanical survey. To a lesser degree, implications of this work may affect or inspire future spectroscopic surveys of extra-terrestrial environments that may host suspended communities of microorganisms.

7.2 Background and methods

There are several tens of hot springs and pools in Long Valley Caldera, all located east of Highway 395. Little Hot Creek (LHC) and Rhyolite Hot Spring (RHS) were chosen for in-depth geobotanical analysis due to their accessibility and differing characters. LHC lies east of the resurgent dome in the central caldera, has the second highest hydrothermal flux in the caldera (behind Hot Creek), and is far more accessible than Hot Creek. LHC is more conducive to uninterrupted sampling and study because it is difficult to find, lies on a fairly rough dirt road, and receives fewer tourists than Hot Creek. RHS is more accessible to the public, but bathing facilities are limited, and the site isn't as aesthetically attractive as other hot springs in the area. These springs have similar pH levels, just below (LHC) or just above (RHS) neutral; but their temperatures are quite different. Surface temperatures at LHC are > 78°C while those at RHS are only 48°C. The flow at RHS is now much less than at LHC, though hydrothermal flow in this region has certainly been higher in the near past. Both sites lie at similar elevations (~2100 m) and are covered in arid desert vegetation including rabbitbrush, sagebrush, antelope bush, salt bush, grasses, and occasional juniper trees. RHS and LHC both have hot pools with cyanobacterial communities, though the populations at LHC are far more prolific and varied. It should also be noted that in the five years (1997-2002) I have studied LHC and RHS, the hot pools and creeks have continuously shrunk in size, desiccating their microorganism populations with them.

I used archival AVIRIS (Advanced Visible Infrared Imaging Spectrometer) images from September 4, 1992; newly acquired AVIRIS data from September 14, 2000; and the seven HyMap flightlines from September 7, 1999. The JPL/NASA AVIRIS datasets were both taken from the high altitude ER-2 platform with spatial resolutions of approximately 17-18m, while the HyMap data, taken at low altitude from a Cessna aircraft, have a spatial resolution of 3-5m. The two AVIRIS datasets differ primarily in their SNR values: in the SWIR (2.0-2.5 um) 1992 measurements had a SNR of ≤ 100:1; while the 2000 imagery reached 400:1 in this same wavelength range. While a higher SNR is ultimately preferable, 1992 AVIRIS data are valuable for assessing the abilities of spacebased hyperspectral imagery with similar low SNR values. For example, the Hyperion sensor has a SNR of less than 50:1 for the 2.0-2.5 um range. Spectral sampling differs markedly between the two airborne sensors: AVIRIS has 224 bands with a fixed bandwidth of 10nm; while the 126-band HyMap sensor has variable bandwidths ranging from 13-17nm across four separate spectrometers. Space borne sensors such as the 220 band Hyperion have bandwidths of 10nm which is the same as AVIRIS.

All analyses in this study were done within the software program ENVI. The images were atmospherically corrected using ATREM (Gao, 1993). Flightlines were subset to separate image cubes that covered each of the two hot spring areas; these were spectrally subset to include only the visible-near-infrared region of the spectrum (0.40-1.8 μm for AVIRIS and 0.45-1.8μm). Two sets of analyses assessed the suitability of hyperspectral imaging to map vegetation communities in hot spring environments. First, the hot springs, pools and associated vegetation communities at LHC were mapped using image-extracted endmembers of various materials and the SAM algorithm. SAM was chosen deliberately for its robust treatment of noisy data (e.g. 1992 AVIRIS). Second, rabbitbrush (an indicator species of high physiological stress) was mapped at and around RHS using ROI-directed, image-extracted spectral signatures in the MF algorithm.

7.3 Results

7.3.1 Vegetation zonation at Little Hot Creek

The Little Hot Creek gorge is bounded on either side by Tertiary sediment cliffs, while the floor of the gorge has small travertine terraces and extensive argillic phase hydrothermal alteration. The pools and creeks of the gorge host thermophilic communities of algae and bacteria with distinct zonation of plant species. Figure 3-18 illustrates the five biological zones generally observed in the vicinity of Long Valley hotsprings and pools. The zones tend to form concentric bands around the spring in a “bulls-eye” pattern. Similar biological zones were described by Brock (1978) in Yellowstone hydrothermal discharge zones.

Zone I

The hot springs and pools lie in the middle of these “hot-spring bulls-eyes”. Hydrothermal waters in the caldera are primarily chloride-bicarbonate rich waters that are neutral to slightly alkaline. While some waters may be slightly acidic, a pH below 6.0 has not been measured at any spring. Temperatures are generally below boiling, though some Hot Creek pools do reach the boiling point for this elevation (~93°C). Such hydrothermal environments encourage colonization by microorganisms, including algae, cyanobacteria, and diatoms (Figure 3-19A,B). These microorganism communities are highly dependant on temperature and chemistry of the host waters and hence tend to be indicative of the general geochemical nature of a hot spring or pool.

Zone II

Soils devoid of vegetation usually surround the hot pools and creeks, except where creeks have incised into the ground more than ~ 15 cm and grasses and sedges grow on the banks above the hydrothermal waters. The soils generally have high concentrations of various evaporites, low to high temperature clays, and dessicated microorganisms from previous times of hydrothermal water inundation. These materials give the soils a whitened, “bleached” look and hence a high albedo compared to the surrounding environment.

Zone III

The bleached soils are surrounded by grass and sedge communities. These Grammanoids are known to withstand higher temperatures than most other vegetation species (Larcher, 1995). While this heat-tolerance allows them to grow close to hot pools and creeks, these grasses and sedges are not immune to extreme heat, and premature senescence and death occurs commonly in these communities.

Zone IV

Rabbitbrush surrounds and often interdigitates with the grass and sedge communities. Rabbitbrush is also a stress-tolerant species that is often found growing along roadways. An irregular border of rabbitbrush surrounds all actively discharging hot springs in Long Valley and is the prime indicator species for hot spring mapping and delineation in the caldera. Though present at all known, currently discharging springs and pools, rabbitbrush is also present in many other bulls-eye zonation locations that currently see no discharge. This probably indicates previous discharge at these sites.

Zone V

The rabbitbrush from Zone IV grades into Zone V, which consists of mixed sagebrush-antelope bush communities, with sparse populations of Juniper and Pinyon Pine. Junipers are usually dominant in this zone over Pinyon, possibly due to Juniper's tolerance of saline stress, which is prevalent in and near arid hot springs.

The SAM algorithm was applied to small subsets of all three years of hyperspectral imagery covering the LHC region. Image-extracted spectral endmembers of various vegetation types (sagebrush, rabbitbrush, grass), soils, and microorganisms were applied to the data. Figure 3-19C shows spectral signatures extracted from a hot pool with extensive cyanobacteria communities. The AV92 signature is taken from the 1992 AVIRIS data and represents data with poor SNR < (400:1), coarse spatial resolution (17-18 m), and a spectral bandwidth of 10nm. The AV00 signature is from the 2000 AVIRIS data with a higher SNR (900:1) and the same spatial resolution and bandwidth as the 1992 data (17-18m and 10nm respectively). In contrast, the HyMap spectral signature has a SNR of 1200:1 and a spatial resolution of 5 meters at this elevation. Though much less noisy, the HyMap data has a coarser sampling bandwidth at 13 nm for this wavelength range - spectral signature detail is traded for higher signal. The final signature in Figure 3-19C is a cyanobacterial spectrum taken in the field with a handheld GER spectroradiometer at LHC. The GER samples at 2nm intervals, and thus this signature is the least noisy and most detailed of the four shown in Figure 3-19C.

The microorganism, vegetation, and soil signatures were each extracted for each year and applied to their respective images to produce SAM classifications (Figure 3-20). These classifications were used to determine 1) whether the imagery detects and maps the vegetation zonation, especially the microorganisms, and 2) whether spatial resolution and SNR affect such determinations. Figure 3-20A shows Spectral Angle Mapper (SAM) results for 1992 AVIRIS imagery that has 17-18m pixels and a SNR of ~ 400:1. Figure 3-20B is 2000 AVIRIS data, also with 17-18m pixels, but with a SNR of ~ 900:1. Figure 3-20C is HyMap data with a 3-5m pixel and a SNR of roughly 1200:1.

The zonation pattern can be discriminated in all three datasets, though the HyMap image possesses the most detail, consistent with its 5m pixel. The microorganisms (Zone I) map as the red and magenta colors, while the dark greens are grasses (Zone III) and the lighter greens are rabbitbrush (Zone IV). Cyan is a mix of sagebrush and soils, while the blues and yellows correspond to dominantly sagebrush found along steep slopes in shade (Zone V). Most of the hot pools are less than approximately $100m^2$. Since the pixels of AVIRIS cover an area of approximately $300m^2$, it is impressive that such small features were mapable in images with the lowest spatial resolution and lowest SNR (i.e. 1992 AVIRIS). The spectral signature for cyanobacteria has a very distinctive geometry and a prominent absorption at 0.62µm due to the pigment phycocyanin (Karnieli and Sarafis, 1996). While, not all of these results have been field-checked, image-extracted signatures from the red and magenta pixels show this 0.62µm feature, and hence likely contain substantial proportions of cyanobacterial mats. 1992 AVIRIS data is similar to that data expected from such satellite sensors as Hyperion. Hence these results suggest that simple vegetation zonation patterns and communities of thermophilic organisms indicative of hydrothermal discharge may be identifiable from space-based hyperspectral sensors. The presence of such microorganisms may indicate current hydrothermal discharge. Such communities desiccate when water levels drop; however, their spectral signatures remain intact (in Zones I and II). Thus, their presence also indicates that thermal waters have flowed over the surface either presently or in the near past.

7.3.2 Vegetation zonation at Rhyolite Hot Spring

Rhyolite Hot Spring has a much lower flow rate than Little Hot Creek. Currently, the hot spring discharges into a wide grassy area, forming one small hot pool that is filled with cyanobacteria mats and algae. A 10-15 meter wide swath of rabbitbrush surrounds the grassy area, and this grades out into sagebrush. Figure 3-21A shows the general RHS landscape. Because the hot pool at RHS is small (< 2 meters in diameter), detection of microorganisms was not possible. However, RHS does host one of the largest, and oldest groves of rabbitbrush in the caldera. Individual bushes rise to almost 2 meters in height and have trunks with ~20cm diameters. The old age of this community suggests long-lived hydrothermal fluid flow at this spring.

Rabbitbrush is a stress-tolerant species and its presence in the caldera usually indicates one of several situations. First, rabbitbrush is found in all hot spring/creek/pool areas, where it is confined to a 20-30 meter zone surrounding the thermal feature. Second, rabbitbrush also grows quite extensively around the Alkali Lakes of the eastern caldera where waters are cool and fairly alkaline and soils have high salt contents. The Alkali Lakes waters permit growth of only a few species, including rabbitbrush, several grasses, and various microorganisms within the mud of the lakes region. Rabbitbrush’s salt and dessication tolerance also allows it to colonize disturbed roadsides where winter road-salting allows for massive salt buildup within the road easements. Third, rabbitbrush is found in many places with no present day thermal or other fluid flow; but these regions usually have salt/sulfate rich soils, indicating probable fluid flow at some time in the past.

The close association of rabbitbrush with thermal or saline waters makes it a desirable mapping target with remotely sensed imagery, and the combination of rabbitbrush with altered soil and microorganism spectral signatures is even more desirable as it narrows the environment of growth to either thermal springs/pools or alkaline waters. Figure 3-21B shows spectral signatures of rabbitbrush. The black signature was extracted directly from the 1999 HyMap imagery. This signature is an average of five pixels from a location in the imagery that was known from the field to have high rabbitbrush densities. In summer 2000, a GPS point taken at the center of the RHS rabbitbrush grove was used to locate the grove the HyMap imagery (Figure 3-21C shows RHS as it appears in the HyMap imagery). Spectral signatures were extracted from this initial GPS point and four other pixels surrounding it. The red signature shown in Figure 3-21B is from the USGS spectral vegetation library and was taken with a handheld spectroradiometer. The main deviations between the image-extracted signature and the USGS signature are in the visible wavelengths, and in the SWIR. The deviation in the visible is due partly to over-corrections in the ATREM atmospheric model used on the HyMap data, and partly to mixing of soil and vegetation in the pixels that reduces the overall reflectance in the visible. The SWIR deviation is due to cellulose/lignin absorption at 2.10 μm in the image-extracted signature that is not present in the USGS signature. The image-extracted signature is of whole bushes (including the stems and bark of the plants), while the USGS is from a close-up measurement of leaves using only a handheld instrument. However, the image-extracted signature appears similar enough to the USGS spectra to classify this signature as rabbitbrush.

This image-extracted signature was then used in a supervised MF classification of the image subset in Figure 3-21C. Figure 3-21D shows the results of this analysis. The brightest red pixels are the best matches to the reference spectral signature in Figure 3-21B. The RHS rabbitbrush grove is mapped quite well, as are populations along the shores of the Alkali Lakes and several populations along the NE-SW roadway. All three of these areas were ground-checked and found to contain rabbitbrush. West of RHS, the classification appears to break down. The wide, north-south trending strip of supposed rabbitbrush does not exist, and is populated with primarily sagebrush-antelope bush communities. Reasons for this mis-classification are not known. One possibility is that the extracted signature contains not only rabbitbrush, but the underlying substrate. As the substrate changes spatially, the classification probably breaks down. The correctly classified rabbitbrush regions are all on similar substrates (alluvium and sandstones/conglomerates), while the falsely classified regions to the west are located on the Hot Creek Rhyolite flow (Qmrh). This mis-classification appears to be geology related.

7.4 Discussion and conclusions

Associative vegetation mapping in geothermal areas was fairly successful, though deserving of further refinement and study. Supervised classifications attempting to discriminate grasses from rabbitbrush were only partially successful, probably due to the fine spatial and intergradation transition between the two and the consequent pixel mixing involved. As angiosperms, grass and rabbitbrush all possess the same absorption-causing biochemicals (esp. chlorophyll), thus their basic signatures are not unique, but are modified more by plant architecture than anything else. It may be this fundamental quality of rabbitbrush that allowed for the partial success in mapping it near RHS. However, the lack of discrimination between grass and rabbitbrush also appears to be more a function of spatial resolution. Far less pixel mixing occurs in 5 meter HyMap data than in 17 meter AVIRIS data. In conclusion, optimal vegetation zonation mapping requires high spatial resolution that captures community scales and transitions and spectral sampling that adequately addresses the width of spectral absorptions of interest.

I successfully mapped limited distributions of microorganism communities at Little Hot Creek. These organism communities, though small in aerial extent, are important indicators for the presence of thermal waters in geothermal environments. This study was only concerned with simple detection of these organisms, however they possess narrow life thresholds and many species possess unique absorptions from molecules present only in subsets of these microbial groups. We did not explore the possibility that groups or even species may have unique, identifiable spectral signatures, so while detecting microorganisms is useful for mapping, identifying and distinguishing among groups may indicate the chemical and/or thermal environments in which they live. Studies coupling spectroscopy with field sampling and identification would further our understanding of microbial spectroscopy. The detection and mapping of the microorganisms was due primarily to the uniqueness of biochemicals, which produced signatures distinctive from those of green plants surrounding them. The differing SNR levels in this study indicate that

SNR was not an issue in detecting microorganisms, rather spatial resolution was. Again, this is likely due to the biochemicals involved.

Such knowledge should be useful not only for terrestrial studies and their implications for biotechnology and geothermal exploration endeavours, but also for extra-terrestrial exploration of other planets/moons. The spectral signatures of microorganisms are unique enough that given a high spectral sampling (narrow bands), future space-based exploration spectrometers may be capable of detecting such extra-terrestrial life.

8.0 General discussion

8.1 Commonalities and differences across systems

Each system discussed has a unique set of environmental variables that create regions with spectrally detectable and in some cases, identifiable materials. The systems differ in their host vegetation and geology, but each experiences strong geological forcing that modifies inherent properties of the ecosystems. Heat, anomalous CO_2 concentrations and flux, acidification, and salinization are present in at least one of the sites, although combinations of these environmental pressures are more common. For example, sustained flux of anomalous CO_2 eventually leads to acidification of soils.

There are commonalities among the systems explored in this study, as well as differences. The conifer forests of the CO_2-induced tree-kill on Mammoth Mt, the grasses and bushes of the Casa Diablo geothermal system, and the microorganisms, grasses, and bushes of the hot spring regions all receive continuous, relatively constant levels of geological forcing. CO_2 degasses from Mammoth at a fairly constant rate, while thermal inputs from fumaroles and hot springs at Casa Diablo and LHC/RHS is also fairly constant on ecological time scales (though fumaroles and hot springs are known to cease, move or begin spontaneously with the correct geological impetus such as crust-shifting earthquakes). All of these regions exceed thresholds of heat/acidity/CO_2 etc. where the input of these forcings becomes stressful to organisms. Those regions that lack vegetation today (such as at the main flux point of CO_2 on Mammoth Mt. or right next to fumaroles at Casa Diablo), were areas that once hosted vegetation, that became physiologically stressed from one or more sustained stressors and ultimately died.

In each system, there are visible transitions between regions lacking vegetation and adjacent regions with unhealthy vegetation, although the manner in which they are expressed differs. A halo of unhealthy, living trees around the main kill zone at Horseshoe Lake marks this zone of transition; while at Casa Diablo, artificially senescent grasses surround the fumarole zone lacking vegetation. The hot springs have non-vegetated zones that grade into healthy grass and rabbitbrush communities. The forcings were probably not initially stressful to all parts of the system (spatially or in temporally). For example, the initial pulse of CO_2 at Mammoth probably acted as a true stressor on the trees inhabiting the original and strongest flux points and may have killed trees there, but nearby trees bordering these areas did not die for another four years. The living halo zone trees, mapped using hyperspectral imaging in this study, may or may not ever die. At Casa Diablo the grasses that prematurely senesce in the spring are doing so because of heat input to the ecosystem, but grasses should grow back in the same locations year after year.

Acidification and salinization of soils at both tree-kill areas and hot springs may take many years to develop their full potency, and hence vegetation in these regions may not become truly physiologically stressed in such environments until long periods of time have passed.

Duration of a particular forcing probably leads to differences in vegetation within a site. Hydrothermal environments have probably existed throughout the history of life, and whole communities of hydrothermal-specific organisms and associated vegetation have evolved. Anomalous CO_2 fluxes regions are much rarer and ephemeral on the surface of the earth, and there is no evidence for specific CO_2-adapted organisms living there. Though long-lived high CO_2 flux regions may select for vegetation tolerant to CO_2 in the long run, they have not spawned new species tolerant to CO_2 that are spectroscopically detectable. Hence, successful remote sensing of CO_2 regions depends on detection of stressed vegetation populations, while remote studies of hot springs has the advantages of unique, thermally-tolerant biological zonation patterns and thermally-adapted organisms.

8.2 The utility of the hyperspectral approach

In all the systems studied, hyperspectral imaging provides either new information or new ways to detect and map responses of vegetation to geological forcing. Each system highlights particular pros and cons for vegetation mapping and characterization, while considering the results together outlines sets of tradeoffs that are involved. In general, hyperspectral imaging is an automated, synoptic, rapid, in-depth assessment and mapping tool, but it is also initially expensive, computationally demanding, and time intensive. For many purposes, the results and benefits from hyperspectral imaging surveys far outweigh the initial cost of imagery and computing time. This is certainly true for mineral mapping, where vast areas of the surface of the earth can be mapped and characterized for mineralization of special interest to geothermal, mining, or other industries. However, the utility of hyperspectral imaging in vegetation characterization is less straightforward. The increased complexity of vegetation spectroscopy is one of the main factors contributing to this ambiguity, largely because of the variation within biological systems at very small scales and short time periods.

Most higher plants have very similar sets of absorptions across species and communities, and discriminating among them is difficult based only on absorption minima and spectral position. Unlike most mineral and anthropogenic material detection and discrimination, which is based on such simple geometric analysis, plant discrimination depends heavily on age, size, season, habitat, physiological state, plant architecture, and usually requires additional groundtruth information. Such characteristics and habitat factors obviously vary over very short time periods and small spatial scales. Thus methods for vegetation analysis are already constrained in many ways, and inherently they require more site-specific work to extract useful information. For example, while mapping hot spring communities and associated biological zonation patterns was successful in this study, without site-specific groundtruth information, their interpretation would have been far less informative.

Hyperspectral vegetation analysis is an iterative process, in which initial characterizations are nearly always followed by refinement of the classifications using added spectral or groundtruth information. The halo-communities around the Horseshoe Lake tree-kill are a perfect example. The spectral signatures for dead and healthy trees were extracted and identified easily, but the signature that eventually was identified as coming from halo communities was not initially recognized. Post-analysis fieldwork revealed that the pixels containing the halo signatures contained trees with just the barest visible signs of physiological stress (generally chlorosis and loss of needles) and lay on the edges of the main kill-zone. The halo spectral signature alone does not reveal this circumstance of incipient kill; the geographical knowledge was essential for interpolation of the signature. For this reason, automated spectral mapping, which is so useful and accurate in mineral characterizations, is often less successful with vegetation. Hyperspectral imaging of vegetation is inherently more complex and time consuming, requiring expert knowledge of both the environments and the organisms being studied. Lack of time and required knowledge bases may make such surveys impractical for some questions or studies.

However, the wealth of information revealed by hyperspectral imaging in a given amount of time, is vastly greater than that gleaned from traditional field-based or other remote sensing studies. Remote sensing technology is superior to field-based methods in its ease and efficiency of many kinds of mapping and characterization. For example, weeks of field mapping of tree-kill and other vegetation boundaries would have been needed to duplicate results that came from hours of processing time with hyperspectral imagery. While some things are obvious to a trained observer on the ground were not detected in the imagery, other properties, seen in the imagery, were not visible on the ground. Alhough complex, hyperspectral remote sensing provides synoptic images that contain large amounts of information, and should lead to entirely new ways of looking at vegetation and other organisms on ecosystem scales.

Hot spring ecosystems provide another example of the wealth of information available from hyperspectral imaging, and of the difficulties inherent to getting it. Biological zonation was mapable in the Long Valley hyperspectral datasets (section 7.0), but required significant fieldwork, including field spectroscopy, before it could be interpreted. For example, spectral signatures of microorganisms are not included in any publicly available spectral library. Hence, identification of these organisms required field collections: the organisms were detected automatically, but were not automatically identified. In addition, the pattern of grass grading into rabbitbrush which then graded into sagebrush was not gleaned from analysis of spectral signatures alone: the spectra of grass, rabbit and sagebrush are too similar. Instead, classes generated automatically in the analyses were later fieldchecked and assigned manually to their respective vegetation type or community. Hence, while hyperspectral imaging provides an entirely new means of mapping hot spring communities, it is still field intensive. However, purely ground-based studies tend to miss the regional zonation patterns readily detected from the air, and the imagery analyses made the fieldwork much more efficient by identifying and mapping likely sites.

The placement of hyperspectral imagers on space-based platforms will make imaging less expensive and continued studies of the kind included in this work, will continue to expand spectroscopic catalogue and best practices, methods, and analysis tools.

9.0 Conclusions

Hyperspectral remote sensing serves as an entirely new way of looking at vegetation and more importantly, vegetation on a community scale. Spectrum-based detection and mapping of vegetation community boundaries was explored throughout this study. The results from detection of tree-kills at Horseshoe Lake revealed that automated detection of dead-tree areas is possible, although more subtle characteristics of tree-health required further, in-depth spectral analysis techniques. Analysis of the geometries of individual spectral endmembers allowed us to determine what was actually being mapped in the supervised classifications such as SAM. However, many useful results came from more automated techniques, such as vegetation indices, that also successfully mapped dead tree areas. Indices only use two bands to determine the relative health of vegetation communities, while SAM classifications use the whole spectrum (450-2500 nm) to distinguish different classes of physiological health based on the magnitudes of several different absorptions or lack thereof. Both ratios and MNF-based techniques may be more robust as a first-cut tree-kill mapping effort, as they require little time and are relatively insensitive to species differences. However, some knowledge about the communities being mapped makes the SAM classifications both more data-rich and more insightful than the techniques that use only limited numbers of bands. Thus, while dead tree areas were adequately mapped using automated techniques like MNF, more useful information was gleaned from further, more in-depth classifications such as SAM.

Multi-temporal tracking of Horseshoe Lake tree-kill boundaries through time was successful, though fairly time consuming. A convincing pattern of growth of kill areas was produced from six separate years of aerial photography and hyperspectral imagery. The kill began in 1990, grew steadily until 1994, then it almost doubled in size. This doubling is attributed to the time required for trees to die when exposed to high but not immediately lethal CO_2 levels on the borders of main flux points. This study also supports the hypothesis of prior acid-loading of Horseshoe Lake soils from earlier CO_2 releases, based on the qualitatively observed sparseness of pre-kill trees in the Horseshoe region (using the 1977 photograph). The success of this study provides an impetus to complete a similar study of the entire Mammoth Mt. region, to ascertain when other kills appeared, and their subsequent rates of growth. Such information may elucidate the locations of main pathways of CO_2 flux on the mountain and provides evidence about deep structural controls on all fluid movements, including magma.

Grass communities in fumarolic fields were studied on the ground with field spectroscopy, and compelling relationships between grass spectral geometries and relative ground temperature were documented. Though only detectable in the late spring in this mid-latitude, arid environment, the results suggest that these changes in spectral geometry with respect to temperature would be readily detectable in airborne hyperspectral imagery. No hyperspectral imagery with the necessary spatial and spectral resolutions exists for this time period in Long Valley Caldera, but a spring acquisition in either Long Valley or a similar geothermal area, would test the methodology and may provide a new geobotanical exploration tool for geothermal power production.

Little research has been done with microorganism spectroscopy under field conditions. The fine spatial resolutions necessary to study such environments were not available for either air or space-based studies until very recently. In addition fine spectral sampling is necessary to identify the pigment absorptions characteristic of the main groups of microorganisms. In this study, hot spring communities were measured both with ground and air-based spectrometers, and the results suggest such communities are detectable and identifiable from air and (by proxy) from space-based platforms. The identification of the unique absorption due to phycocyanin allows for mapping of cyanobacterial mats not only in Long Valley, but probably also in other terrestrial geothermal areas. This phycocyanin absorption is just one of many absorptions found in hot spring microbes, and suggests that more work in this area is warranted.

Airborne hyperspectral imaging is currently a relatively expensive, field-intensive tool for vegetation study, but its synoptic, rapid, and in-depth analyses may outweigh the initial cost and fieldwork. In the future, such acquisitions will become more routine and cheaper. Our understanding of biological spectroscopy will continue to increase, and our methodologies and algorithms will improve. Inherently, vegetation and other organisms possess a level of variability not seen in the geological world. This will always make biological studies more complex, but ultimately more information rich.